NACA

RESEARCH MEMORANDUM

for the

Air Materiel Command, Army Air Forces

PERFORMANCE OF J-33-A-21 AND J-33-A-23 COMPRESSORS
WITH AND WITHOUT WATER INJECTION

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NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS

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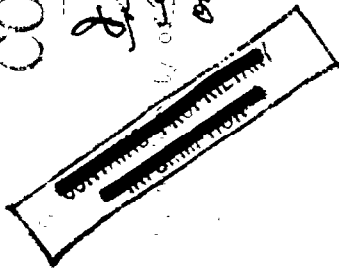
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SUMMARY

In an investigation of the J-33-A-21 and the J-33-A-23 compressors with and without water injection, it was discovered that the compressors reacted differently to water injection although they were physically similar. An analysis of the effect of water injection on compressor performance and the consequent effect on matching of the compressor and turbine components in the turbojet engine was made. The analysis of component matching is based on a turbine flow function defined as the product of the equivalent weight flow and the reciprocal of the compressor pressure ratio.

With water injection the surge point of the J-33-A-21 compressor occurred at a lower value of the turbine flow function than without water injection; the compressor therefore should not operate in the surge region when water is injected. The surge point of the J-33-A-23 compressor occurred at a higher value of the turbine flow function with water injection than without. This compressor operating under normally stable conditions without water injection may move into the surge region or into a condition of unfavorable operation by addition of water unless the pressure ratio for normal operation is less than 94 percent of the peak pressure ratio.

INTRODUCTION

At the request of the Air Materiel Command, Army Air Forces, an investigation is being conducted at the NACA Cleveland laboratory to determine and analyze the performance of a series of J-33 turbojet-engine compressors. In the course of an investigation of the J-33-A-21 and the J-33-A-23 compressors with and without water injection, it was discovered that the compressors reacted differently to water injection although they were physically similar. An analysis was made of the effect of water injection on compressor performance and the consequent effect on the matching of the compressor and turbine components in the turbojet engine.

ANALYSIS

A flow function governing the performance of the turbine component of the J-33 turbojet engine is $(W\sqrt{T_3/T_0})/P_3/P_0)$ where W is weight flow in pounds per second, T is total temperature in $^\circ R$, and P is total pressure in inches mercury absolute. The subscripts 0 and 3 refer to NACA standard sea-level conditions and conditions at the turbine inlet, respectively. The ratio T_3/T_0 is $T_3/T_1 \times T_1/T_0$, where the subscript 1 refers to the compressor inlet. The ratio T_3/T_1 is an independent variable fixing the operating condition and

$$\frac{T_3}{T_0} = \frac{T_3}{T_1} \times \theta$$

where

$$\theta = \frac{T_1}{T_0}$$

The ratio

$$\frac{P_3}{P_0} = \left(\frac{P_3}{P_2}\right)\left(\frac{P_2}{P_1}\right)\left(\frac{P_1}{P_0}\right) = \left(\frac{P_3}{P_2}\right)\left(\frac{P_2}{P_1}\right)\delta$$

where

$$\delta = \frac{P_1}{P_0}$$

and subscript 2 refers to the compressor outlet. If there are small losses through the burner, P_3/P_2 is nearly unity; then

$$\frac{W\sqrt{T_3/T_0}}{P_3/P_0} = \left(\frac{W\sqrt{\theta}}{\delta}\right)\left(\sqrt{\frac{T_3}{T_1}}\right)\left(\frac{1}{P_2/P_1}\right) \tag{1}$$

Therefore, $\left(\frac{W\sqrt{\theta}}{\delta}\right)\left(\frac{1}{P_2/P_1}\right)$ determines approximately the flow function governing turbine performance for a given value of T_3/T_1.

This analysis neglects the effect of change in gas properties and weight flow with the addition of fuel or water. The addition of fuel or water would cause the turbine flow function to be somewhat greater than that given by equation (1). The change in specific heats arising from changes in the composition and temperature of the gas is also neglected.

RESULTS

The variation in over-all pressure ratio with equivalent weight flow for the J-33-A-21 compressor is presented in figure 1. Water injection increased the over-all pressure ratio approximately 9.5 percent and the equivalent weight flow approximately 7.0 per-

cent. The addition of water moved the surge point of
the compressor to an air weight flow approximately 6.0
percent greater than that without water injection.

The variation in over-all pressure ratio with
equivalent weight flow for the J-33-A-23 compressor
is presented in figure 2. The over-all pressure ratio
was increased only 3.0 percent, whereas the equivalent
weight flow increased approximately 13.0 percent. The
addition of water moved the surge point of the com-
pressor to an air weight flow approximately 17.0 per-
cent greater than that without water injection.

The variation of the pressure ratio of the two com-
pressors with the turbine flow function $\left(\dfrac{W\sqrt{\theta}}{\delta}\right)\left(\dfrac{1}{P_2/P_1}\right)$
is presented in figures 3 and 4. The addition of water
in the J-33-A-21 compressor (fig. 3) caused the surge
point to occur at a value of $\left(\dfrac{W\sqrt{\theta}}{\delta}\right)\left(\dfrac{1}{P_2/P_1}\right)$ approxi-
mately 3.0 percent lower than the corresponding value
without water injection.

The addition of water in the J-33-A-23 type com-
pressor (fig. 4) caused the surge point to occur at a
value of $\left(\dfrac{W\sqrt{\theta}}{\delta}\right)\left(\dfrac{1}{P_2/P_1}\right)$ approximately 15.0 percent
greater than the corresponding value without water in-
jection. The opposite trends in the displacement of
the surge point for the two compressors is partly due
to the fact that the increase in pressure ratio ef-
fected by water injection was 6.5 percent greater for
the J-33-A-21 compressor than for the J-33-A-23 com-
pressor.

DISCUSSION OF RESULTS

Two significant effects of water injection on
the operation of the jet engine are: (1) a change in
over-all compressor pressure ratio and (2) a change in
the magnitude of the turbine flow function
$\left(\dfrac{W\sqrt{\theta}}{\delta}\right)\left(\dfrac{1}{P_2/P_1}\right)$. When the pressure ratio across the

turbine exceeds approximately 2:1, sonic or nearly
sonic velocities can be expected in the turbine nozzles.
At compressor pressure ratios above 3:1, the pressure
ratio across the turbine will almost certainly be
greater than 2:1. At the design speed of the compressor
therefore, sonic velocities can be assumed to exist
in the turbine nozzles if the turbine is reasonably
well matched with the compressor. The value of the

flow function $\left(\frac{W\sqrt{\theta}}{\delta}\right)\left(\frac{1}{P_2/P_1}\right)$, which is nearly proportional

to the Mach number at the inlet of the turbine nozzles,
will thus be constant for all values of compressor
pressure ratio greater than that required for obtain-
ing the critical turbine pressure ratio. The operating

value of $\left(\frac{W\sqrt{\theta}}{\delta}\right)\left(\frac{1}{P_2/P_1}\right)$ would therefore be almost un-

affected by the injection of water into the compressor.
On this basis, injecting water into the J-33-A-21 engine
will result in higher compressor pressure ratios and
higher values of $W\sqrt{\theta}/\delta$, both of which will have
beneficial effects on the thrust of the engine. On
the other hand, injection of water into the J-33-A-23
engine will tend to make the compressor operate at
lower weight flows than that for the surge point unless
the compressor pressure ratio for normal operation
is less than 94 percent of the peak pressure ratio.
Although the effects of such operation cannot be
predicted from the present data, the over-all result
will certainly be less beneficial than that antici-
pated for the J-33-A-21 engine.

SUMMARY OF RESULTS

An investigation of the performance of the
J-33-A-21 and the J-33-A-23 compressors with and
without water injection produced the following results:

(1) The surge point of the J-33-A-21 compressor
with water injection occurred at a lower value of the
turbine flow function than without water injection.
The operation of this compressor in the surge region
is therefore not anticipated.

(2)   The surge point for the J-33-A-23 compressor
with water injection occurred at a higher value of
the turbine flow function than without water injection.
This compressor operating under normally stable con-
ditions without water injection may therefore move
into the normal surge region or into a condition of
unfavorable operation by the addition of water unless
the compressor pressure ratio for normal operation
is less than 94 percent of the peak pressure ratio.

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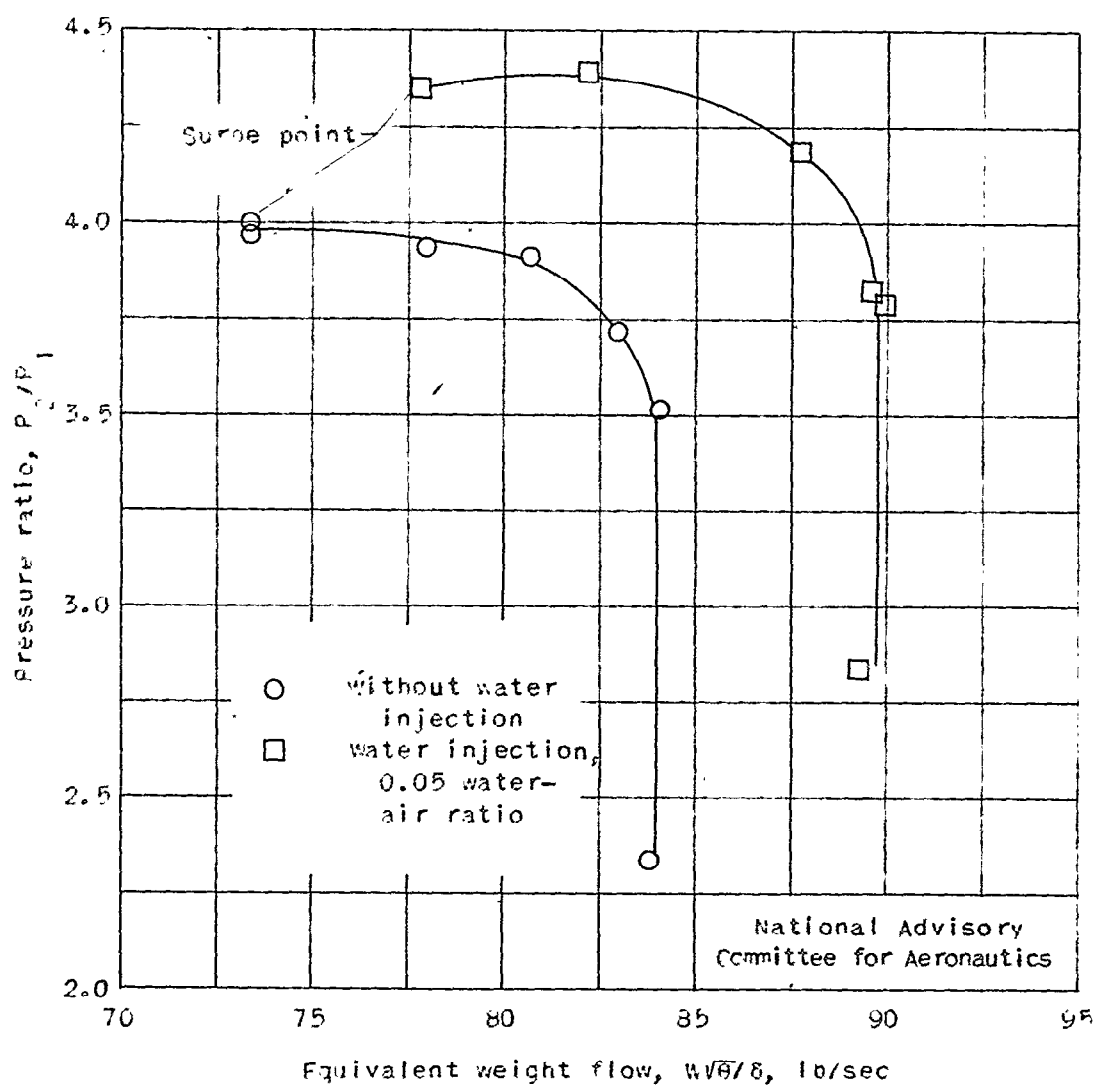   Mechanical Engineer.

            Oscar W. Schey,
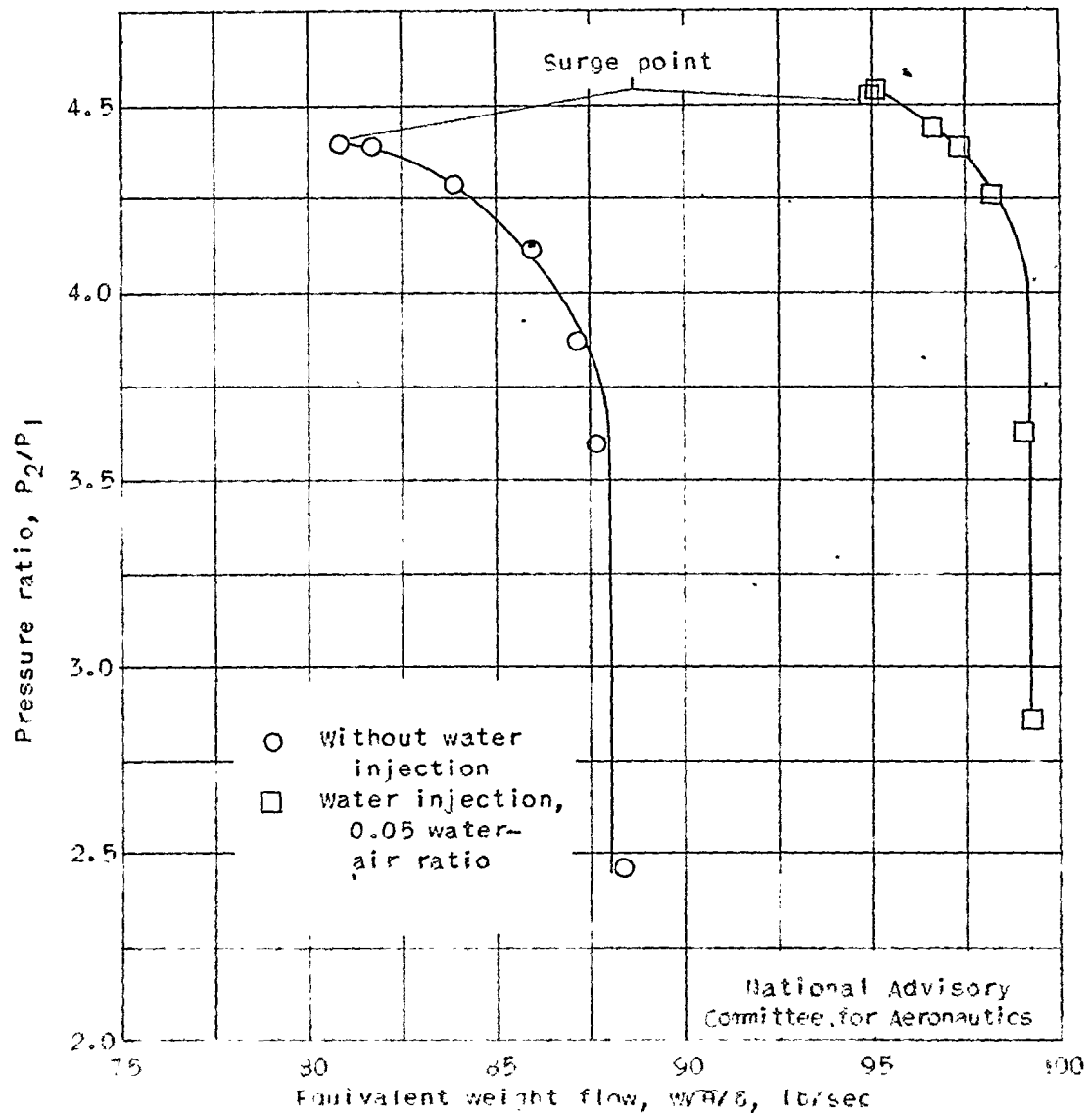   Mechanical Engineer.

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Figure I. - Variation of over-all pressure ratio with equivalent
weight flow for J-33-A-21 compressor at inlet temperature of
80° F, inlet pressure of 14 inches mercury absolute, and de-
sign speed of 11,500 rpm.

Figure 2. - Variation of over-all pressure ratio with equivalent
weight flow for J-33-A-23 compressor at inlet temperature of
80° F, inlet pressure of 14 inches mercury absolute, and speed
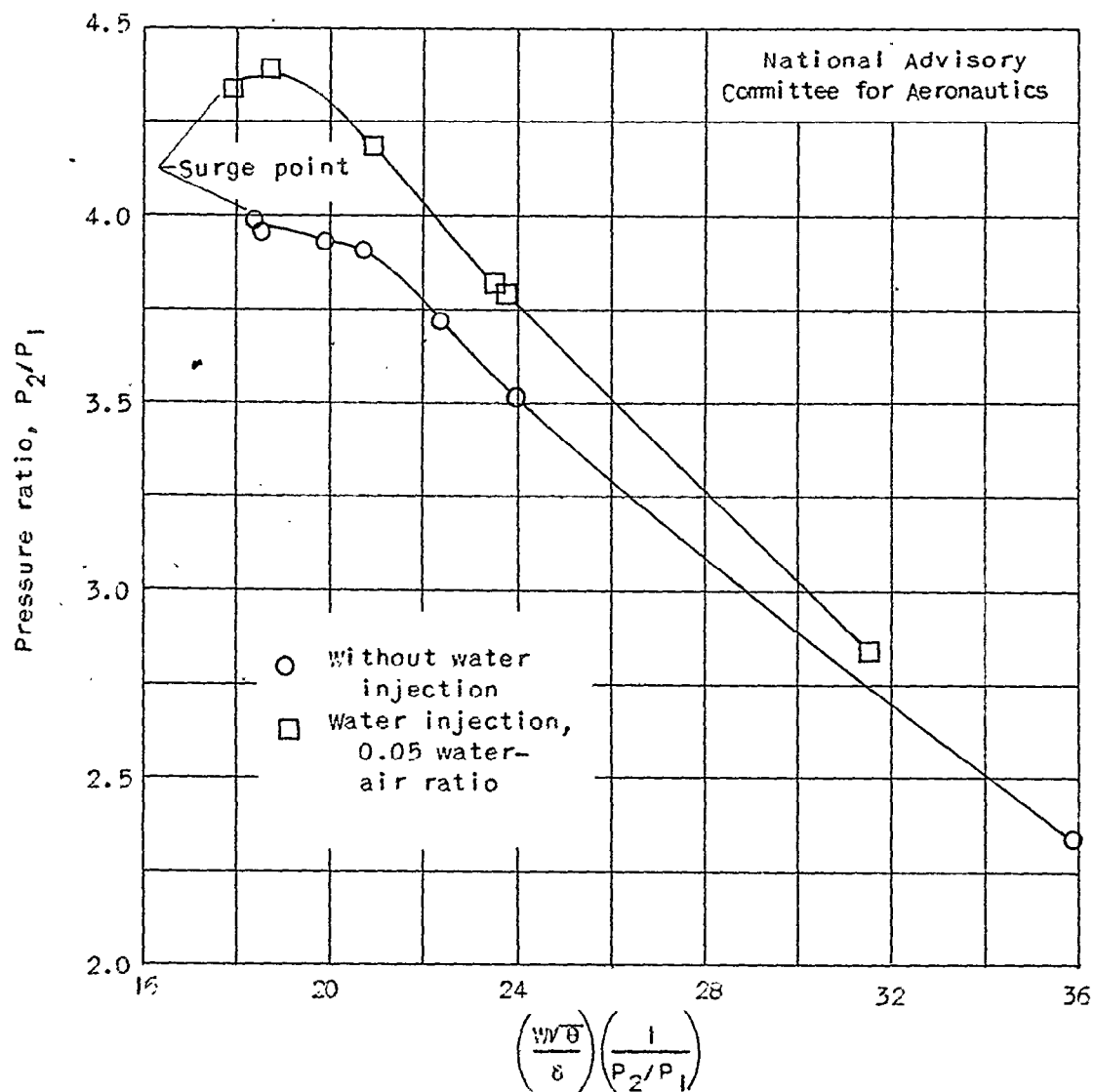of 11,750 rpm.

Figure 3. — Variation of over-all pressure ratio with $\left(\dfrac{w\sqrt{\theta}}{\delta}\right)\left(\dfrac{1}{P_2/P_1}\right)$ for J-33-A-21 compressor at inlet temperature of 80° F, inlet pressure of 14 inches mercury absolute, and design speed of 11,500 rpm.
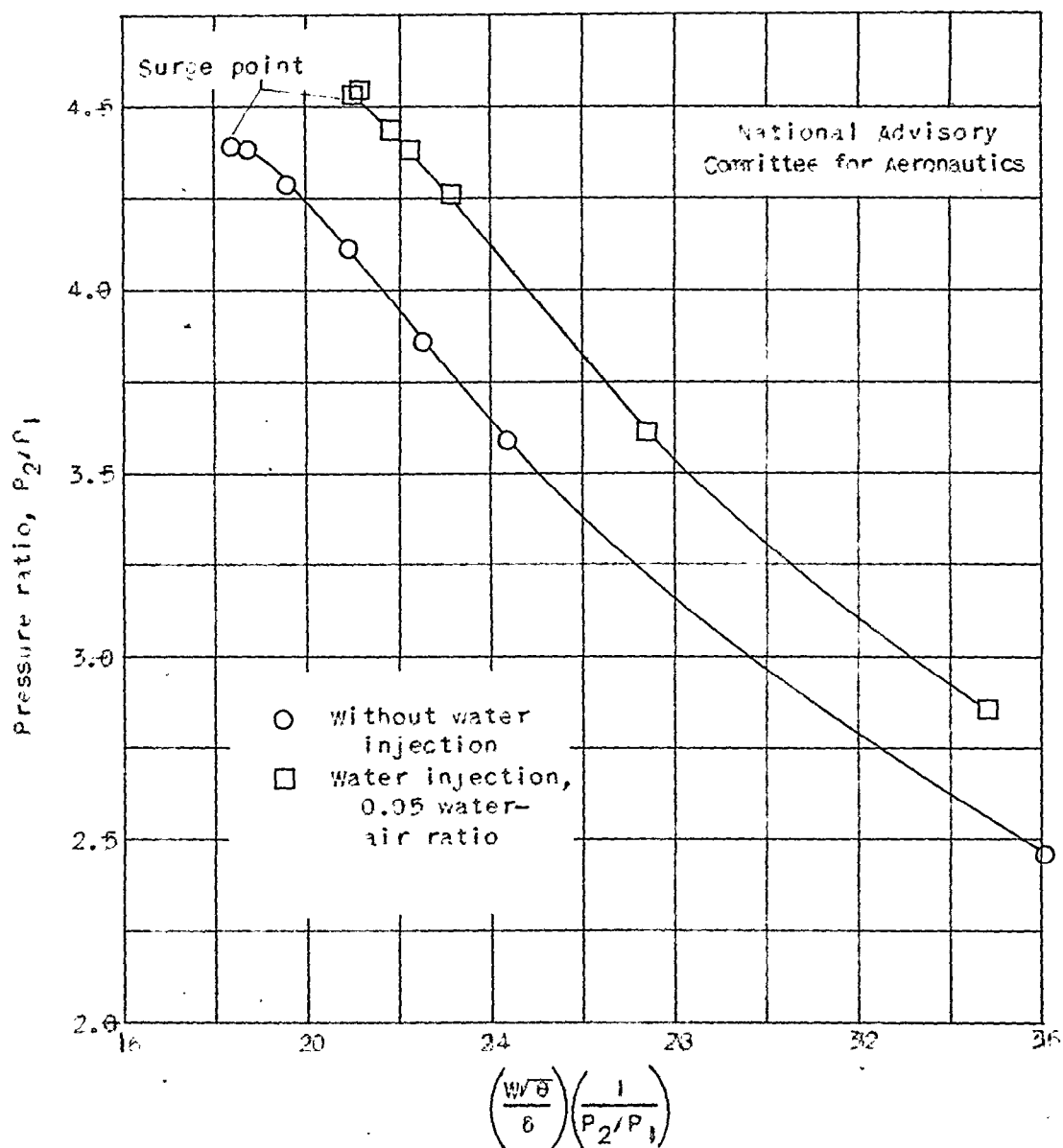
Figure 4. - Variation of over-all pressure ratio with $\left(\dfrac{W\sqrt{\theta}}{\delta}\right)\left(\dfrac{1}{P_2/P_1}\right)$ for J-33-A-23 compressor at inlet temperature of 80° F, inlet pressure of 14 inches mercury absolute, and speed of 11,750 rpm.